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Past Deep-ocean Circulation and the Paleoclimate Record–Gulf of Cadiz

Deep marine currents are strongly influenced by climatic changes. They also deposit, rework, and sort sediment, and can generate kilometer-scale sedimentary bodies (drifts). These drifts are made of thoroughly bioturbated, stacked sedimentary sequences called contourites [*Gonthier et al.*, 1984]. As a consequence, change in the direction or intensity of currents can be recorded in the sediments.

The Gulf of Cadiz represents the pathway of a strong, warm (13°C), and saline (> 37 g l^{-1}) current called the Mediterranean Outflow Water (MOW), which comes out of the Mediterranean and spreads in the mid-depth North Atlantic at water depths of 800–1200 m. Its velocity is > 3 m s^{-1} when it flows out of the Strait of Gibraltar (Figure 1). A current named the Atlantic Inflow [*Nelson et al.*, 1999] flows back from the Atlantic into the Mediterranean. The MOW velocity quickly drops from the Strait of Gibraltar, but still reaches 0.2 m s^{-1} at Cape St. Vincent (southwest Portugal).

New, high-resolution bathymetry data presented in Figure 2 were collected during the CADISAR cruise on the R.V. *Le Suroît* (August 2001) using a multi-beam echosounder EM 300. The map covers an area ranging between N35° 35′ and N36° 35′ and W6° 40′ and W8° 10′ (Figures 1 and 2). It shows in detail the complex current activity in this area. Long Calypso piston cores were collected during the IMAGES V cruise with the French research vessel *Marion Dufresne* (September 1999). They allow reconstruction of the past MOW circulation, which was strongly influenced by paleoclimatic changes. This circulation affected the deep-water circulation on a global scale.

Present-day Circulation, Sea Floor Morphology

The new bathymetry and imagery data show that the MOW controls regional sedimentation patterns and explains the general way the Gulf of Cadiz sedimentary system works (Figure 2). When entering the Gulf, a part of the MOW is quickly deflected under the effect of the coriolis force and takes a northwest path [*Madelain, 1970*]. MOW captures particles supplied by Spanish rivers and from the shelf [*Grousset et al.*, 1988]. The particles are entrained and dispersed by the high energetic MOW on the continental slope in the Gulf of Cadiz and to the north beyond. The sedimentary features observed downflow from Gibraltar mirror the progressive decrease of MOW energy [*Kenyon and Belderson*, 1973]. Global grain-size of surface sediment also decreases when MOW velocity and competency (i.e. the ability of the flow to transport detritus in term of particle size) decrease.

Following the MOW westward from the Strait of Gibraltar, gravel lags and giant erosional features (GF in Figure 2) are first observed, and then, sand patches (SP in Figure 2), and sediment waves (SW in Figure 2) with their sand content decreasing westward [*Mélières*, 1974; *Kenyon and Belderson*, 1973; *Nelson et al.*, 1999]. A part of the MOW is channeled by the major, northern, intermediate or southern channels (MC, NC, IC, and SC, respectively, in Figure 2) or by secondary channels (SeC in Figure 2), such as the Gil Eanes channel (GE in Figure 2).

One of these channels follows a tectonic lineament oriented N45° that is associated with topographic highs and lows (DL in Figure 2). Some of the highs are circular and interpreted as diapirs of Triassic evaporites [*Mougenot*, 1988]. Others are escarpments with a more linear trend and represent probably submarine scarps of outcropping rocks or consolidated sediments. Most of topographic lows also have a circular shape. They are interpreted as collapse zones due to dissolution of Triassic evaporites. These observations suggest that the orientation of the south MOW channel, and hence, the flow direction, is locally controlled by tectonic features.

Recent tectonic stress is also documented by the presence of a mud volcano (MV in Figure 2) in the southeastern-most part of the map. On the landward side of the channels, MOW velocity decreases and fine particles deposit, forming thick sediment accumulations such as the Faro (FD in Figure 1) and the Guadalquivir drifts (GD in Figures 1 and 2; *Gonthier et al.*, 1984; *Mougenot*, 1988). They began to grow just after the Messinian (6–5.3 Ma), when the current Mediterranean-Atlantic connection formed [*Faugères et al.*, 1985a].

Another part of the MOW spills over a topographic high (TH in Figure 2) and strongly

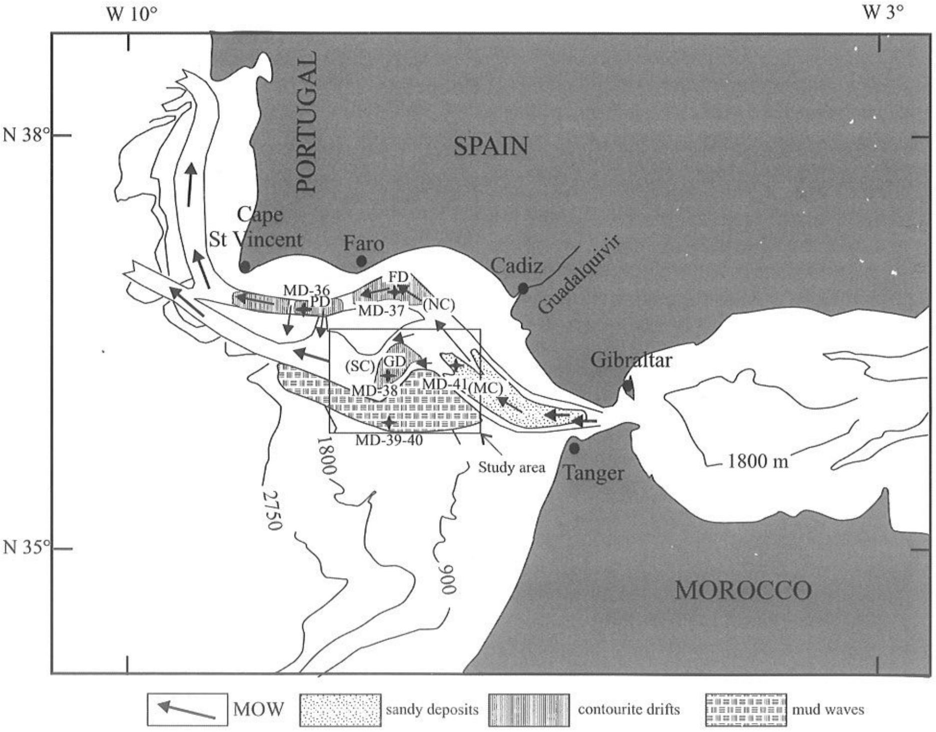

Fig. 1. General map of the Gulf of Cadiz showing the general circulation of the MOW and location of cores MD99–2336, MD99–2337, MD99–2338, MD99–2339, MD99–2340, and MD99–2341. Arrows indicate MOW direction. FD - Faro drift. GD - Guadalquivir drift. PD - Portimão drift.

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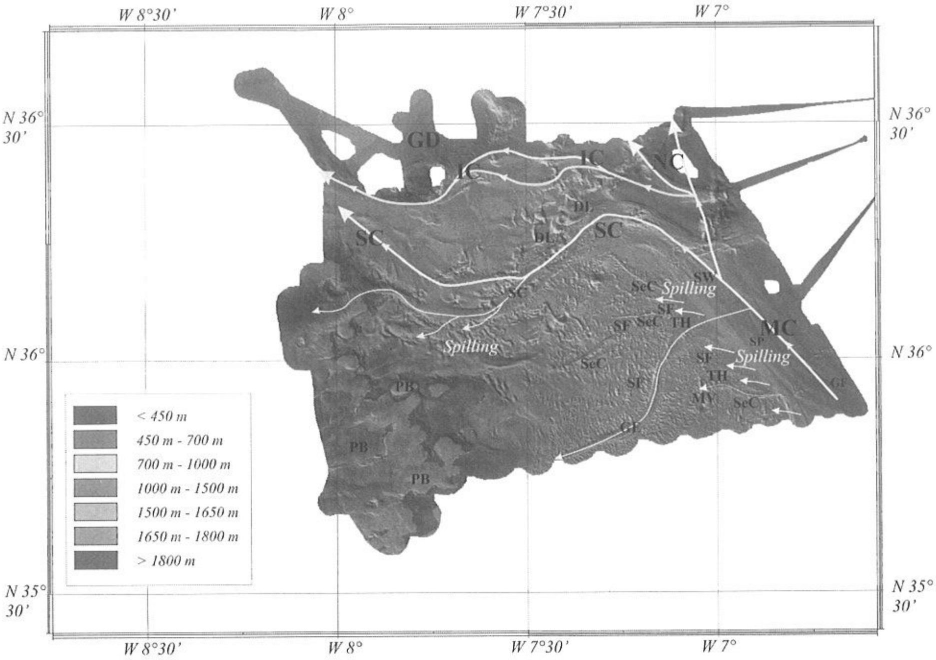

Fig. 2. High-resolution (30 m x 30 m grid) bathymetric map of the south part of the Gulf of Cadiz extending west of Gibraltar. DL - Lineaments of diapirs and rock outcrops. GD - Guadalquivir drift. GE - Gil Eanes channel. GF - Giant erosional features. IC - Intermediate MOW channel. MC - Major MOW channel. MV - mud volcano. NC - North MOW channel. PB - Ponded basins (ancient sediment failures). SC - South MOW channel. SeC - Secondary channel. SF - sediment failure. SP - sand patches. SW - sediment waves. TH - topographic high. Arrows indicate MOW pathway. Map produced using Caraibes software from IFREMER.

decelerates, and deposits particles forming extended fields of sediment waves in the depth interval between 1000 and 1500 m (Figures 1 and 2). This process induces very high sedimentation rates of up to 39 cm ka^{-1} in core MD99–2339 (J. Schönfeld, unpublished data, 2001). These high sedimentation rates and the continuous east-west shearing of surface sediment by MOW induces sediment deformation and failures (SF in Figure 2), with occasional rounded morphology, indicating simple sediment collapse without transport, shallow slumps, or bottleneck sediment flows, according to the terminology of *Prior and Coleman* [1979]. Frequent earthquakes—such as the 1755 Lisbon earthquake [*Zitellini et al.*, 1999]— with their epicenter located in the Gulf of Cadiz or in the neighboring areas, and related to the activity of the accretion prism, probably contributed strongly to the triggering of these slope failures.

They also could be responsible for pockmark formations. These instabilities could be at the origin of the formation of secondary channels such as the Gil Eanes channel by retrogressive erosion. The most western part of the map shows circular to egg-shaped depressions (PB in Figure 2), interpreted as large sediment failures heading westward, and finally forming small ponded basins. The recent discovery of methane hydrates, cold seeps, and gas bubbles in sediment cores from pockmarks suggests that sediment instabilities could also be promoted by methane clathrates fluidizing [*Somoza et al.*, 2002].

Past Circulation and Paleoclimatic Records

Six 20-m-long cores have been collected during the IMAGES V cruises on the high sedimentation rate zones (Figures 1 and 3): the Portimão drift (MD99–2336), the Faro drift (MD99–2337), the Guadalquivir drift (MD99–2338), a mud-wave field (MD99–2339 and MD99–2340), and a landward terrace of the northern channel (NC, MD99–2341). Detailed sedimentological analysis shows that the cores comprise successions of alternating fine- and coarse-grained contourites. Coarse-grained contourites are deposited during periods of increased MOW velocity [*Gonthier et al.*, 1984]. Correlations with shorter cores [*Faugères et al.*, 1985b] suggest that three major periods of MOW acceleration are evidenced in the cores, except on the Portimão drift, where a sedimentary hiatus exists for the interval Boelling-Younger Dryas.

The three periods are noted as peak contourites I, II, and III in Figure 3 and correspond, respectively, to ages of ca. 3000 yrs BP, 10,000–11,000 yrs BP (Younger Dryas and termination IB), and 13,000–15,000 yrs BP (Last Isotopic Maximum and Heinrich Event H1), on the radiocarbon time scale [*Vergnaud Grazzini et al.*, 1989]. During these periods, coarse-grained contourites are associated with high benthic ^{13}C levels and high (smectite + kaolinite)/(illite + chlorite) ratios [*Vergnaud-Grazzini et al.*, 1989]. These periods of MOW intensification are also recorded in benthic faunal and isotope data from the upper Portuguese margin [*Schönfeld and Zahn*, 2000] and correspond to major Northern Hemisphere ice-melting phases with better oxygenation of intermediate waters in the Gulf of Cadiz following the Last Glacial Maximum (LGM, 18,000 yrs BP, or isotopic stage 2).

The period just following the LGM (17,000–15,000 yrs BP) and intervals between 13,000–11,400 yrs BP and 9000–5000 yrs BP are characterized by a finer sedimentation, suggesting a MOW of lesser intensity. The new IMAGES cores confirm the previous results about change in MOW activity since the LGM, and extend the MOW record back in time to 50,068 (MD99–2341) and 91,645 (MD99–2336) calendar years. The average sand content is higher prior to the last Glacial-Interglacial Transition in cores MD99–2338 and MD99–2341 than during the Holocene.

A backward extrapolation of the sand content variations from LGM to the present suggests that MOW velocity was probably higher during isotopic stage 3 than presently. It progressively decreased until LGM for the depth interval between 500–1200 m. This suggests an intensification of MOW during ice melting periods, similar to what happened after LGM. Pulses of energetic MOW during major cold periods (Stadials) are displayed by sand content maxima and contourite beds that alternate with periods of lesser intensity during Interstadials 3 through 12 (Figure 3). This pattern remains consistent further back in time. Oxygen isotope stage 4 in core MD99–2336 (1250–1405 cm) again shows higher sand contents and a bundle of contourite beds.

Gulf of Cadiz is Key

These data suggest that the Gulf of Cadiz is a key area to study this climatic record. Changes and pulses in MOW intensity are accurately recorded by deep-sea sedimentation and related to climatic changes. The sensitivity of the Gulf's sedimentary systems is due to the very strong current, in that the amplitude of change in velocity is sufficiently large to be recorded accurately. Simultaneously, particle supply is high and allows high sedimentation rates that facilitate a high temporal resolution to monitor millennial variations.

Reconstruction of the history of MOW activity is a key point for understanding recent global climatic changes and climate regulation during the Quaternary. The rate of MOW advection presumably is involved with North Atlantic thermohaline circulation THC [*Reid*, 1979], even though the sensitivity of modern THC-to-variable-MOW inputs is controversial [*Johnson*, 1997; *Rahmstorf*, 1998]. Nonetheless, under different—i.e., glacial—conditions with a weakened THC, MOW may well prove to be a key component to understanding rapid climatic changes and climate regulation. The dense Mediterranean outflow increases the density of cold Atlantic deep-water masses, and it may stabilize, or in cases of decreased MOW advection, destabilize the thermohaline circulation, and trigger climate change.

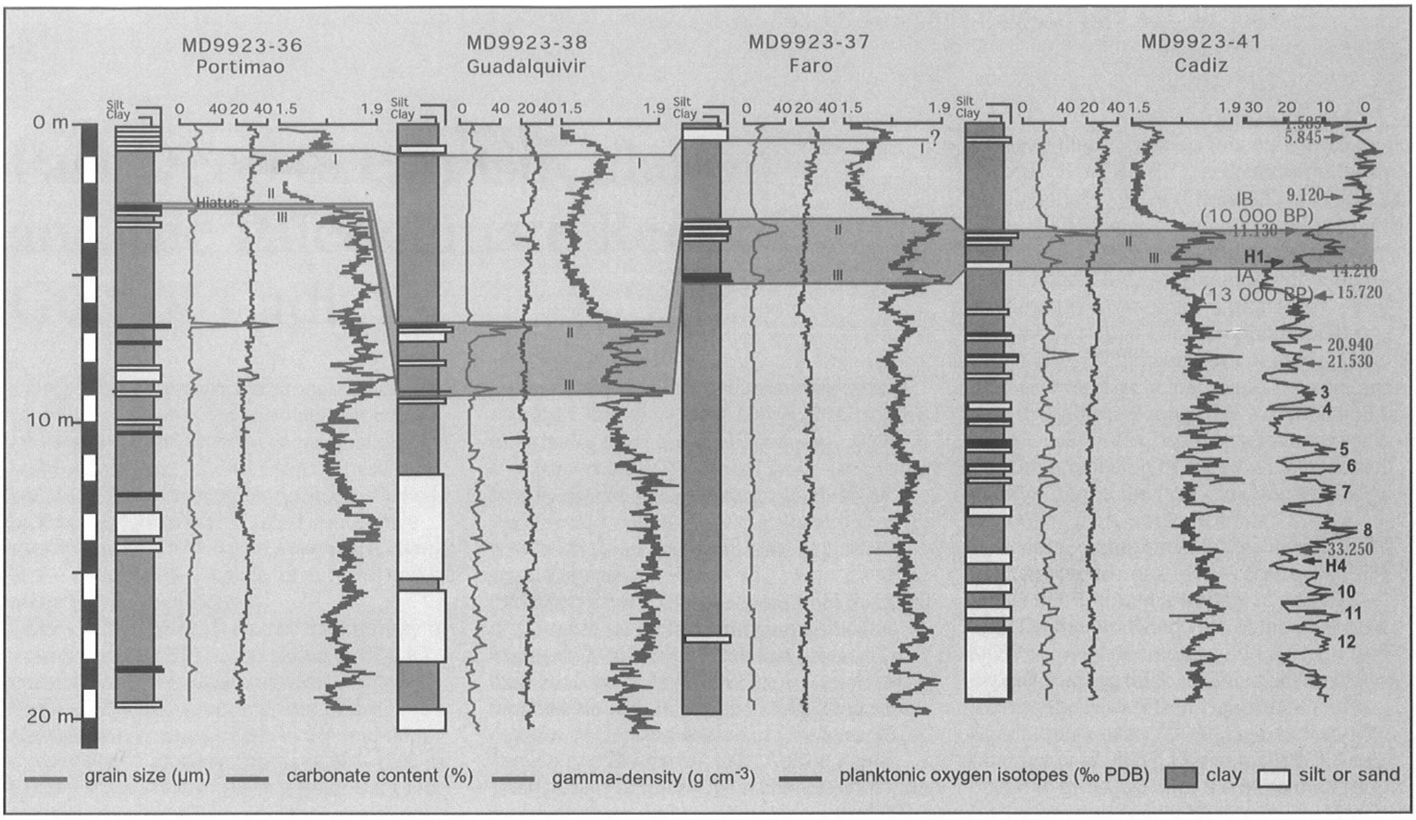

Fig. 3. Synthetic description and stratigraphic correlation for cores MD99–2336, MD99–2337, MD99–2338, and MD99–2341. The arrows indicate levels of ^{14}C AMS dating on planktonic foraminifers in core MD99–2341. Black digits are Interstadial and Heinrich Event numbers.

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